CRYOCOOLER COLDFINGER HEAT INTERCEPTOR

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ABSTRACT

Spacecraft instruments requiring cryocoolers in their design struggle to keep overall power requirements in line with feasible solar array dimensions and launch vehicle lift capacities. Intermediate temperature (150 K to 200 K) radiators to cool radiation shields or optics on spacecraft instruments provide an as yet untapped resource for reducing the cryocooler power requirements.

JPL has demonstrated significant thermal performance improvements to British Aerospace (BAe) cryocoolers by providing passive cooling below 200 K along the warm end of the cryocooler coldfinger. Inclusion of the thermal strap to cool the coldfinger has resulted in 50 % reductions in cryocooler input power with no loss in refrigeration capacity for coldtip temperatures near 60 K. It is clearly shown in this paper that the advantages of a hybrid cooler/radiator design has profound benefits for spacecraft.

INTRODUCTION

Spacecraft instruments using infrared detectors need to maintain the detectors at a stable temperature typically between 10 K and 90 K. Mechanical cryocoolers are required to support multi-year missions, and often redundant cryocoolers are necessary to assure the overall reliability. However, the cryocooler input power required to provide the necessary cryogenic cooling requirements can severely tax the overall available spacecraft bus power. The parasitic heat load placed on operating coolers by the redundant coolers can be a substantial fraction of the available cooling power at cryogenic temperatures if the redundant coolers are to be used without heat switches. This parasitic heat load must be absorbed by the operating cooler, further increasing the power demands of the operating cooler. Extensive thermal design goes into the spacecraft instrument to optimize thermal heat transfer to both the spacecraft thermal radiator and to the detector system. Integration techniques such as those used by the tactical cooler community to integrate detector and dewar to the low power cryocooler help to minimize parasitic conductive losses and increase the amount of useful cooling work that the cooler can perform.

This paper describes a new spacecraft integration approach towards improving the cryocooler's thermal efficiency by using a spacecraft's cryogenic-temperature passive radiator to remove heat from the cryocooler coldfinger. A thermal link from the radiator is attached to a point along

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the coldfinger to intercept the parasitic heat load from the warm end of the coldfinger as well as to reduce the temperature of the gas in the regenerator. The modest amount of heat removed at the coldfinger wall has a significant effect on the measured performance of the cooler. This hybrid cryocooler/radiator design provides significant benefits in overall spacecraft design as well, which can be demonstrated in lowered electrical drive power requirements and reduced mass requirements for the spacecraft solar panel, 300-K radiator, and support structures.

The heat interceptor concept was demonstrated on two British Aerospace (BAe) coolers, the BAe 80 K and the BAe 50-80 K coolers. Incorporation of the heat interceptor was found to produce a significant thermal performance enhancement for each cooler, increasing the thermal efficiency by as much as 100%. This thermal efficiency improvement can be realized as either a reduction in cooler drive power requirements for constant cooling temperature and cooling load, or can enable a combination of lower cooling temperatures and larger cooling loads for the same drive power requirement. This is shown in the experimental results of the next section.

EXPERIMENTAL MEASUREMENTS

Each of the BAe coolers was instrumented and operated in JPL's off-state thermal conductance test facility.[1] In the facility, the coldfinger is enclosed in a vacuum housing together with the coldfinger of a Gifford-McMahon (G-M) cooler, which provides the cold sink for the BAe coldfinger. The test configuration is shown in Fig. 1. The BAe compressor and displacer were mounted to heat sink plates and maintained at 20°C with the aid of a recirculating chiller to insure repeatability between tests. A flexible copper thermal strap was mechanically attached to one of the two stiffening rings machined into the BAe coldfinger, as shown in Fig. 2.

Cooler Thermal Performance Measurements

Each of the BAe coolers was initially operated at nominal compressor and displacer strokes without the thermal strap attached to the coldfinger to obtain a baseline thermal performance loadline against which the subsequent thermal performance loadlines taken with the thermal strap would be compared. The copper flange was attached to the stiffening ring to measure the

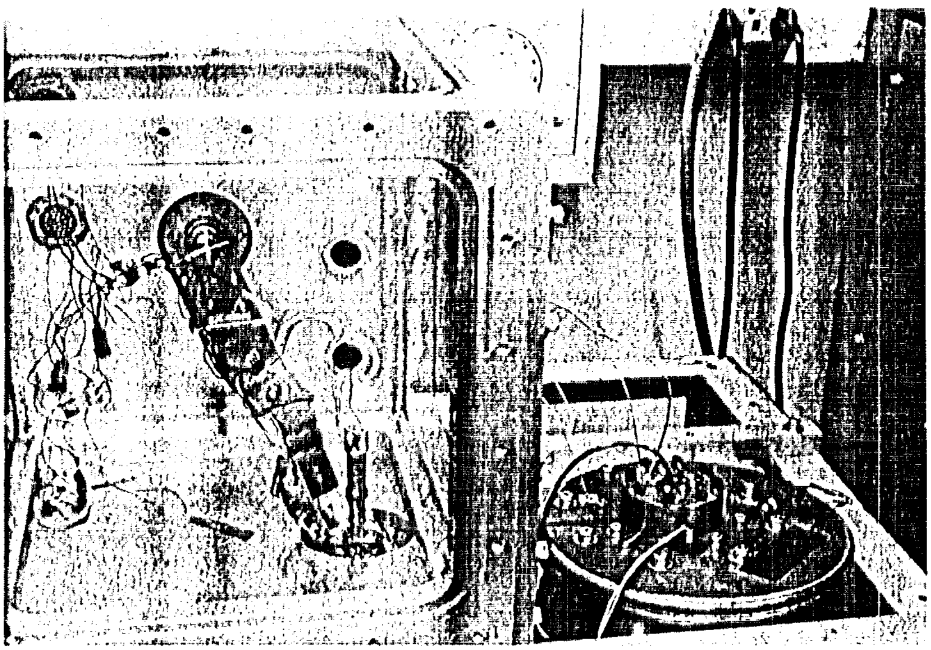

Figure 1. Experimental test set-up for heat interceptor/cryocooler performance measurements.

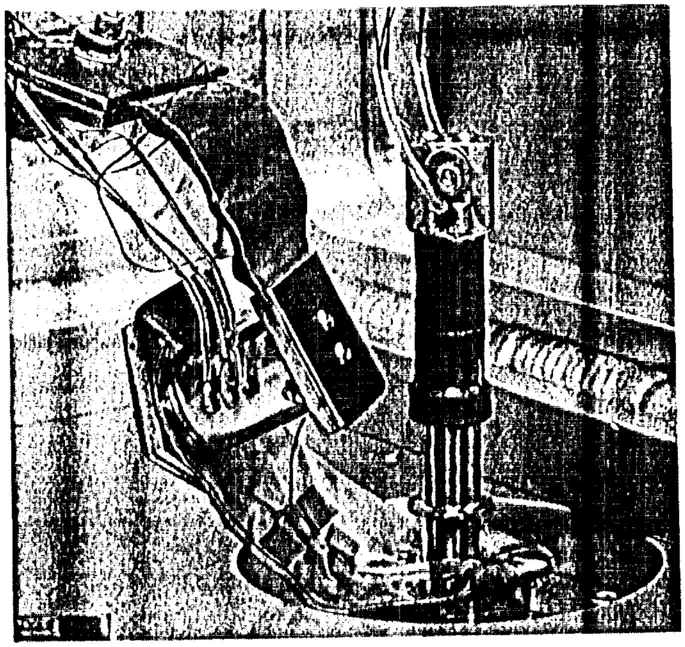

Figure 2. Heat interceptor attachment design for coldfinger stiffening ring.

temperature at the stiffening ring. An indium washer inserted between the stiffening ring and the flange insured good thermal contact. Temperature measurements were made with a silicon diode mounted to the flange. The nominal temperature at this stiffening ring during the baseline cooler operation was ?50 K, and was observed to increase by 10 K over the. range of coldtip loads tested. No attempt was made to maintain the stiffening ring at a constant temperature during the baseline. measurements, thus the. average temperature for the stiffening ring is used on the. subsequent figures.

Next, the. flexible copper thermal strap from the. G-M cooler was attached to the flange on the stiffening ring. The heat-interceptor temperature was regulated using the G-M cryocooler together with a resistive heater cm the. thermal strap driven by a 1'11) temperature controller. The controller was capable of maintaining, the stiffening ring temperature to within 0.1 K. Slow speed stiction tests[2] were run at 0.00?. Hz cm the. cold displacer to verify that the. the.mal strap did not put a sick load onto the coldfinger sufficient to cause displacer rubbing to occur.

With the thermal strap attached to the coldfinger, thermal performance loadlines were. repeated with the same compressor and displacer strokes as in the baseline case while maintaining, the heat intercept temperature at 150 K, and the.n 190 K. This enabled the. determination of the improvement in the. thermal performance. Loadlines were also measured with reduced compressor strokes for both the 1 SO-K and 190-K heat-intercept temperatures to determine the reduction in compressor input power possible while. maintaining a constant cooling load and temperature.

Results of the loadline measurements for the BAe 80 K cryocooler operating under the. different operating conditions arc shown in the multi-variable. plot in Fig. 3. The numbers along the loadlines represent the. measured coldtip temperatures at the specific coldtip loads. The solid line re.presents the. baseline thermal performance of the cryocooler without the application of the heat interceptor to the coldfinger. All other loadlines were taken with the thermal strap attached to the coldfinger stiffening ring and maintaining, a heat intercept temperature. of 150 K or 190 K. This figure emphasizes the reduction in compressor input power possible. when a cryogenically cooled thermal strap is attached to the. displace.] coldfinger. Note that for a 61-K coldtip

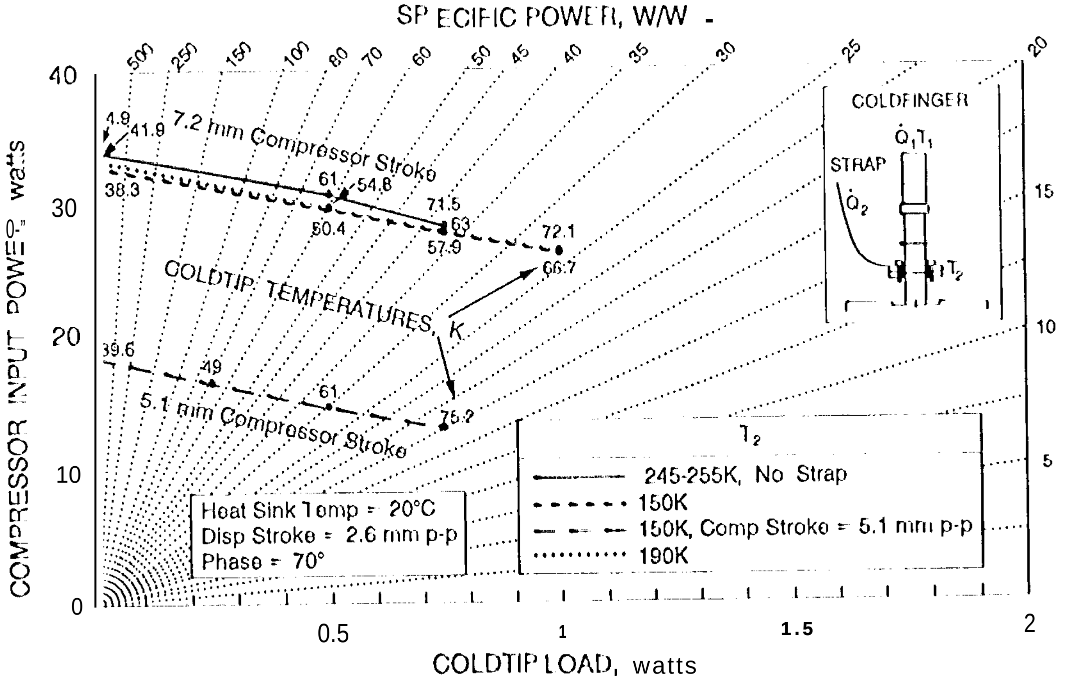

Figure 3. Thermal performance sensitivity of BAe 80 K cooler with heat interceptor.

temperature and a **500** mW coldtip load, the inclusion of the 150-K thermal strap reduced the compressor input power from 30.7 **W** to 14.7 W (a 52 % reduction).

Figure 4 provides a clearer representation of the enhanced coldtip performance obtainable with the heat interceptor while operating the compressor at a constant 7.2-mm compressor stroke. These loadlines show a significant improvement in the attainable coldtip temperature for any

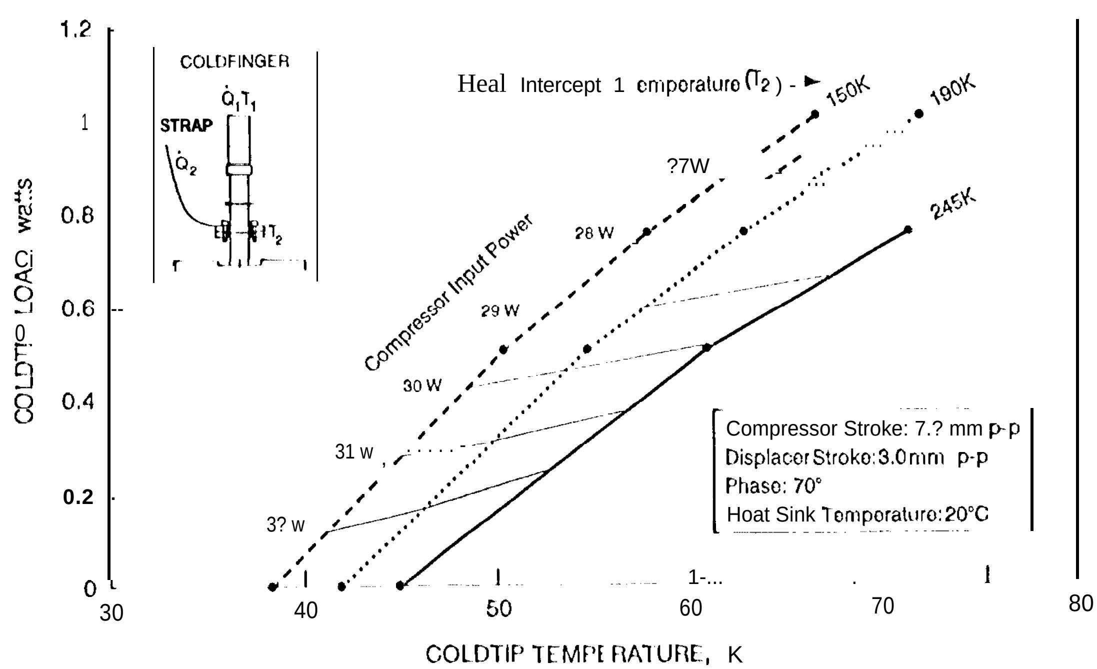

Figure 4. Thermal performance sensitivity at constant stroke. for BAe 80 K cooler with heat interceptor.

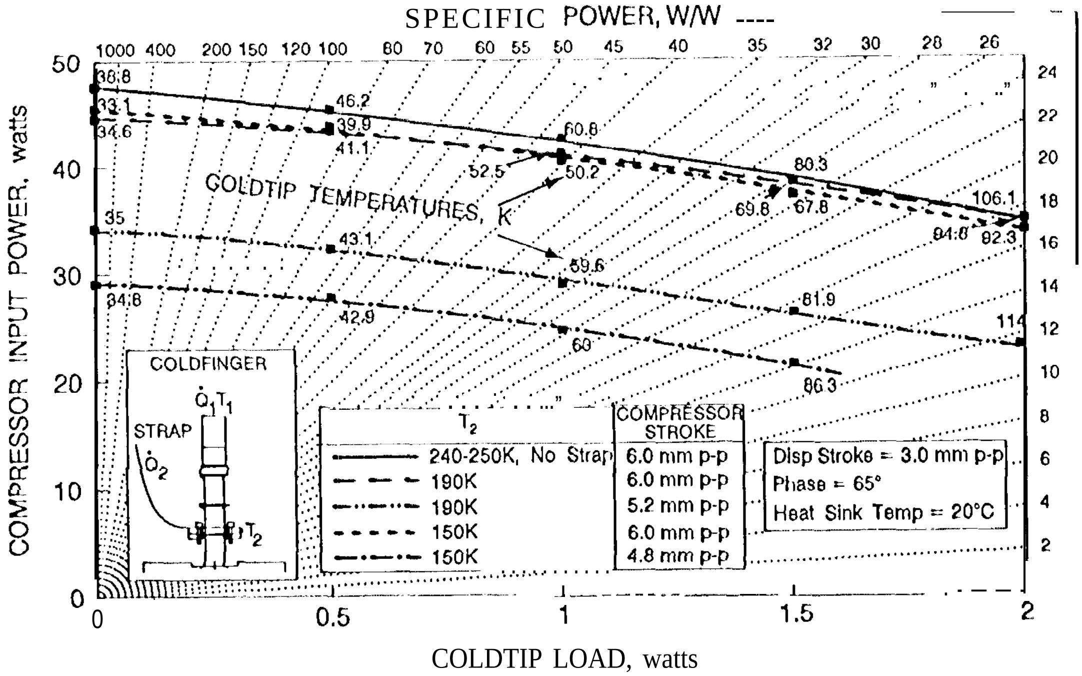

Figure S. Thermal performance sensitivity of BAe 50-80 **K** cooler with heat interceptor.

given cooling load. The loadline curves also show that for a given coldtip temperature as much as 300 mW of increased cooling capacity could be achieved with the 1 SO-K heat intercept temperature, and that this increase in cooling capacity is accompanied with a 3 W decrease in, cooler input power. For a cold tip temperature of 60 K, this results in a net performance improvement of over 75 %,

Results for the BAe 50-80 K cooler loadline measurements arc shown in Figs. 5 and 6. The multi-variable plot in Fig. 5 shows the loadlines measured for the cooler operating with different compressor strokes and heat intercept temperat ures. The solid line represents the baseline performance measure for the cooler. The other loadlines were obtained for the cooler with the thermal strap attached to the coldfinger. Similar to the BAe 80 K cooler, utilization of the 150-K strap while operating the BAe 50-80 K cooler at constant compressor stroke. results in a nominal 10 K reduction in coldtip temperature along with a small reduction in compressor input power. For a 60-K cold tip temperature and a 1 W cooling load, the 150-K heat intercept strap reduced the compressor input power by 15 W over the baseline operation. Figure 6 shows a nominal 300 mW increase in cooling capacity when operating at the 150-K heat intercept temperature, for constant compressor stroke operation of the cooler.

During the testing it was confirmed that the electrical drive power, which is typically very small (<1 watt), was not affected by the addition of the heat interceptor.

Heat Interceptor Calorimetry Measurements

During tests with the BAe 50-80 K cooler, a heat flow transducer was inserted into the thermal path of the heat intercept strap to measure the heat flow out of the. coldfinger wall and into the heat interceptor cold sink. The results are shown in Fig. 7. For 60-K coldtip temperatures the quantity of heat removed via the 190-K heat strap was approximately 1.1 W, and for the 150-K heat strap the heat removed was approximately 1.7 W. The heat flow to the 150-K strap asymptotes to 2 watts for coldtip temperat ures above 100 K.

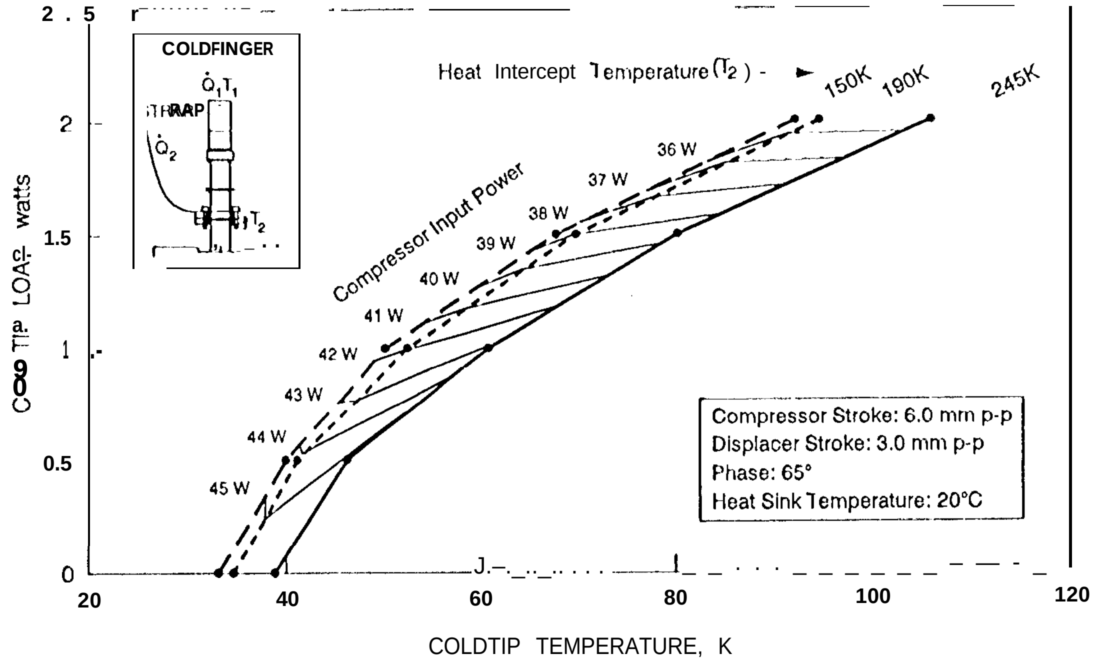

Figure 6. Thermal performance sensitivity at constant stroke for BAe 50-80 K cooler with heat interceptor.

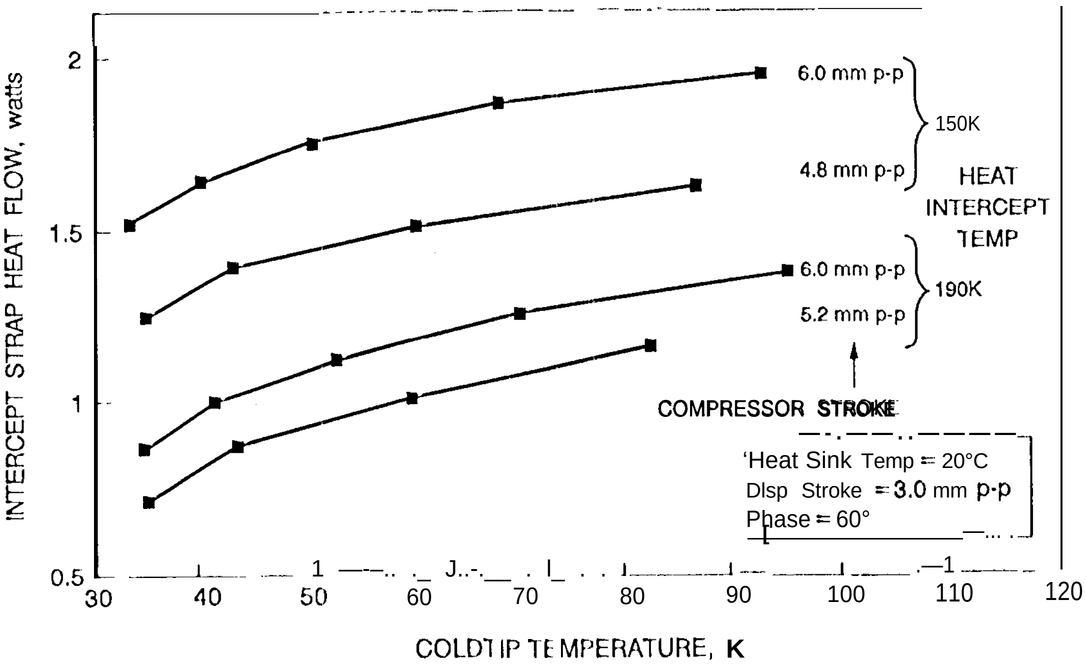

Figure 7. Heat flow through BAe 50-80 K cooler heat interceptor.

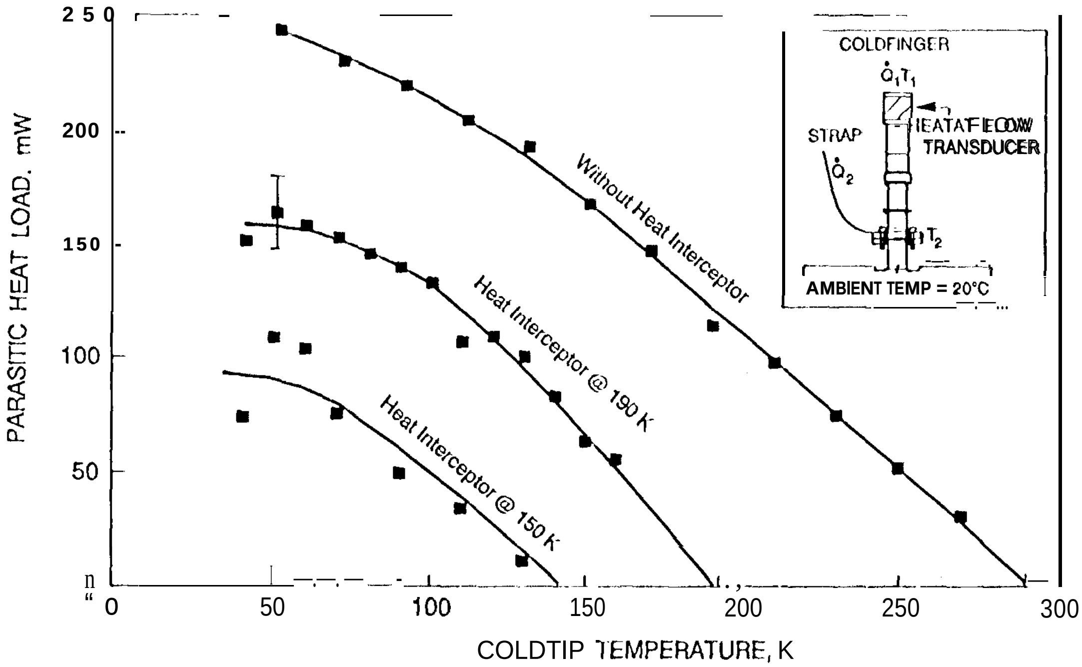

Figure 8. BAe 50-80 K cryocooler coldfinger off-state conduction.

Coldfinger Heat Conduction Measurements

Parasitic heat conduction measurements were made at the coldtip of the BAe 50-80 K coldfinger to determine the change in parasitic heat load along the length of the coldfinger resulting from the attachment of the heat intercept strap. These measurements were made by adding a second G-M cooler to the vacuum chamber, its coldfinger being used to cool the coldtip of the now non-operating BAe cooler to typical flight operating temperatures. “l'he heat flow transducer was inserted into the thermal path to measure the parasitic heat load as a function of BAe coldtip temperature. As expected, there was a significant reduction in the measured parasitic heat conduction for the cases where the heat strap was attached to the stiffening ring. The reduction, shown in Fig. 8, was as much as 150 mW at a coldtip temperature of 50 K (or about 60 %),

SPACECRAFT DESIGN IM1'I.1CA11ONS

The hybrid cooler/cryogenic radiator is applicable for both earth orbiting and deep space missions, and enables several significant design and operational improvements for the spacecraft and the spacecraft instrument. As noted above, the incorporation of the heat intercept strap to transfer heat to a cryogenic radiator can provide significant enhancements to the cryocooler thermal performance. With a 150-K heat intercept temperature applied to the cryocooler coldfinger, cryocooler drive power requirements can be reduced by as much as 50 %, or equally important, the cooling capability of the cooler can be nearly doubled.

For spacecraft instruments which have ruled out mechanical cryocoolers because of the cryocooler input power demands, the inclusion of a cryogenic temperature radiator in the spacecraft design and utilization of the heat intercept strap may be the enabling features that permit the instrument to incorporate cryocoolers to extend mission lifetimes or to enhance mission objectives. The use of the cryogenic radiator could be extended to provide cryogenic thermal shielding about the detector to reduce the radiative load on the detector. For small missions where the parasitic heat load from a redundant cooler may have been comparable to the detector cooling requirement, the utilization of the heat intercept strap would also reduce the parasitic load from the redundant cooler, making its inclusion into the overall thermal design feasible.

Besides the improvement in cryocooler performance, there are also significant spacecraft size and mass savings as well. To assess the potential benefits to incorporating the heat interceptor concept into a spacecraft, it is useful to examine the performance improvement to the BAe 50-80 K cooler as an example. 'l'he measured performance data from Figs. 5 and 7 show that operating the BAe 50-80 K cooler with the 150-K heat interceptor while applying a 1 watt refrigeration load at 60 K, results in a 15-W reduction in cooler drive power and a conduction of 1.5 W from the coldfinger into the 150-K heat strap.

The 15-W reduction in electrical power results in a reduction in solar panel area. Assuming a solar panel with an efficiency of 8% for converting sunlight into electrical power, and a solar constant at earth of 1356 W/m^2, the solar panel electrical power productivity is approximately 110 W/m^2. This suggests an associated 0,136 m^2 reduction in solar panel area. There is an accompanying reduction in storage battery size as well (the storage battery is needed to continue the operation of the spacecraft as it passes through the earth's shadow).

For low earth orbiting spacecraft, cryogenic radiators are capable of operating at temperatures around 150 K to 180 K, Radiator performance is highly orbit dependent and mission dependent, but for this example assume that the cryogenic radiator is at 150 K, and that both the 150-K and 300-K radiators have an emissivity of 0.9 and radiate. to deep space. The 15-W power reduction also means a 15-W reduction in heat being dissipated from the cooler to the 300-K radiator, resulting in a 0.036 m^2 decrease in the size of the 300-K radiator. The 150-K radiator will require a 0.058 m^2 increase in size to dissipate the additional 1.5-W load at this radiator.

These dimensional changes can better be assessed in terms of the mass adjustments to these components. Mass allocations typically used[3] for the solar panel/storage batteries and for the 300-K radiator is 0.25 kg/W and 0.1 kg/W, respectively. The 15-W power reduction therefore corresponds to a potential mass reduction of 3.8 kg for the solar panel and 1.5 kg for the 300-K radiator. Using a T^4 ratio to estimate a corresponding mass allocation of 1.6 kg/W for the 150-K radiator, the additional 1.5 W of heat rejection at 150 K would add 2,4 kg to the mass of the 150-K radiator. The net decrease in mass suggests there could be a potential reduction in mass for the support structure for the solar panel and radiator. The order of magnitude difference in the heat flow (1.5 W vs 15 W) between the 1 SO-K thermal strap and the 300-K thermal strap (or mounting interface structure) carrying the rejected heat to the respective radiators suggests there could be considerable savings in mass there as well, Assuming, for example, that both thermal straps were made of copper 20 cm in length and had an end to end temperature drop of 5 K, the associated change in mass would be 4.8 kg for the 300-K thermal strap and 0.48 kg for the 150-K thermal strap. The estimated mass savings is summed up in Table 1.

Table 1. Example mass savings resulting from use of 150-K heat interceptor.

Component	Mass Change
Solar Array/Battery	-3,8 kg
300 K Radiator	-1.5 kg
150 K Radiator	+2.4 kg
Compressor to Radiator Thermal Conductor	-4.8 kg
Heat interceptor to Radiator Thermal Strap	+ 0.5 kg
S/C Support Structure	unknown
Net Mass Savings	7.2 kg

For deep space missions it is possible to reject heat at temperatures as low as 40 K. This provides the opportunity to reject heat from the coldfinger at even lower temperatures, or to reject the heat from the first stage of a two stage coldfinger. This is expected to further reduce cooler drive power requirements, potentiall y enabling the use of < 10-K cryocoolers for deep space missions.

A reduction in input power to the cryocooler translates into operating the cryocooler piston and/or displacer at reduced stroke. This provides another benefit to the spacecraft as it results in a reduction of the cryocooler-generated vibration and EMI levels being transmitted to the spacecraft, and as well, reduces the stress on the flexure springs which can effect the overall reliability of the cooler.

SUMMARY

The test results presented above show the significant performance improvements, as much as 100%, with the British Aerospace cooler when incorporating the cold finger heat interceptor. The stiffening rings on the BAe coldfinger provided a convenient and near optimal attachment point for the thermal strap. Here the parasitic load along the coldfinger wall was easily intercepted and removed. It is anticipated that additional performance improvements could be made for any given heat intercept temperature through an optimization of the regenerator matrix or by determining the optimum attachment point along the length of the coldfinger. It is expected that the performance improvements may be even more profound for external regenerator displacers and pulse tubes, where the regenerator and working gas is in intimate contact with the coldfinger wall.

The utilization of the thermal heat intercept strap to transfer a modest amount of heat from the cryocooler coldfinger to the spacecraft cryogenic radiator can provide substantial thermal efficiency improvements that translate into reductions in the electrical power and mass for the spacecraft design. The hybrid cooler/cryogenic radiator can allow low power missions to now include a cryocooler into the design without a major power penalty, or to include a redundant cryocooler to prolong mission life.

ACKNOWLEDGEMENT

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